Using Aftershock Relocations and 3D Mechanical Models to Understand the Integrated Behavior of Normal, Antithetic and Strike-Slip Faults During Crustal Extension

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Investigations Undertaken

We proposed to develop conceptual and quantitative mechanical models that address the following fundamental questions regarding the occurrence and effects of active normal fault systems: 1) how is crustal extension accommodated by normal faults, linking strike-slip faults, and antithetic faults; 2) how does such a system of faults interact in time and space through the perturbed stress fields associated with earthquakes on individual faults or several fault segments; and 3) what part of this process can be explained by brittle deformation as computed using models that idealize the constitutive properties to linear elastic, but honor the resolvable complexities of fault geometry? Seismic, geodetic, and geologic data for this study comes from the 1995 Kozani-Grevena earthquake. Relocations of aftershocks has been completed and clearly focuses these events onto a pattern of normal, antithetic, and strike-slip faults that apparently trigger one another and act in concert to accommodate regional extension. Geomechanical modeling of this better-resolved fault array is underway.

We also proposed to develop the mechanical models based on a boundary element method (BEM) computer code, Poly3D, using the solution for angular dislocations in a linear elastic half space. To facilitate our investigation of the Kozani-Grevena earthquake data, and to make this code available to and usable by the community of researchers in academia and at the USGS, we developed a graphical user interface, Poly3DGUI. This is a versatile numerical modeling tool for the mechanical analysis of active faulting in three dimensions. Poly3D approximates complex fault surface shapes and irregular tiplines using triangular elements, thus avoiding the topological errors encountered with conventional rectangular dislocation elements. We believe that the geometric versatility of triangular elements will provide new insights concerning fault interaction, and a better accounting of the partitioning of regional strain onto the faults.

The 2001 panel summary for this proposal explicitly stated that: "The proposal was voted for one year of support at full funding, with the strong expectation that Poly3D be released to the community no later than the end of the funded year." With that admonition we adjusted some of our management plan (see below) enabling us to release the beta version of the interface in mid-August of this year. About 45 geologists and geophysicists expressed interest in using the code at a poster that previewed potential applications and features during the Fall 2001 AGU Meeting. An email announcement went to all of these investigators with information about the release and how to download the beta version. In addition, a burst email was sent to the SCEC database of investigators with the same information. Both Poly3D and Poly3DGUI are downloadable from our web site at no charge as long as the usage is intended for non-commercial purposes (see details of the downloading procedure at the end of this report).

The management plans for 2002 called for development and testing of the core code (Poly3D) for friction and fault-zone properties. This activity has been started, but the completion of this effort has been postponed to the second year in order to accomplish two other objectives. The first was to get the numerical code and GUI in the hands of researchers as soon as possible. Establishing a web site for public downloading of the beta version of the code was listed as a second year activity, but was moved into the first year and has been completed. The URL for this site is:

http://pangea.stanford.edu/geomech/Software/Software.htm

To further this objective we have presented results from applications of the codes at the October 2002 Geological Society of America Meeting in Denver, and will present additional results at the December 2002 American Geophysical Union Meeting in San Francisco (see abstracts listed below). The second objective was to implement a new 3D slip inversion algorithm, which has significant potential for earthquake studies (see below).

Results

Kozani-Grevena Earthquake Relocation

Using the Double Difference algorithm (Waldhauser and Ellsworth, 2000) we have relocated 650 of 666 aftershocks recorded on a local network deployed for one week after the Kozani-Grevena earthquake (Hatzfeld et al., 1997). The relocation method improved hypocentral locations by a factor of ~10, yielding clusters of aftershocks along a network of normal, antithetic, and oblique-slip faults.

We have constructed a Poly3D model based on our interpreted fault pattern and used forward modeling to compare predicted surface displacements with InSAR observations (Fig. 1). The model results are generally consistent with the InSAR observations, with most of the slip on the east-west normal fault, creating an elongated area of subsidence. We are in the process of using the newly created inverse modeling module in Poly3D (see below) to invert for slip on each of the interpreted faults and thus make a more quantitative evaluation of our fault model. This work is on scheduled for completion by the end of 2002.

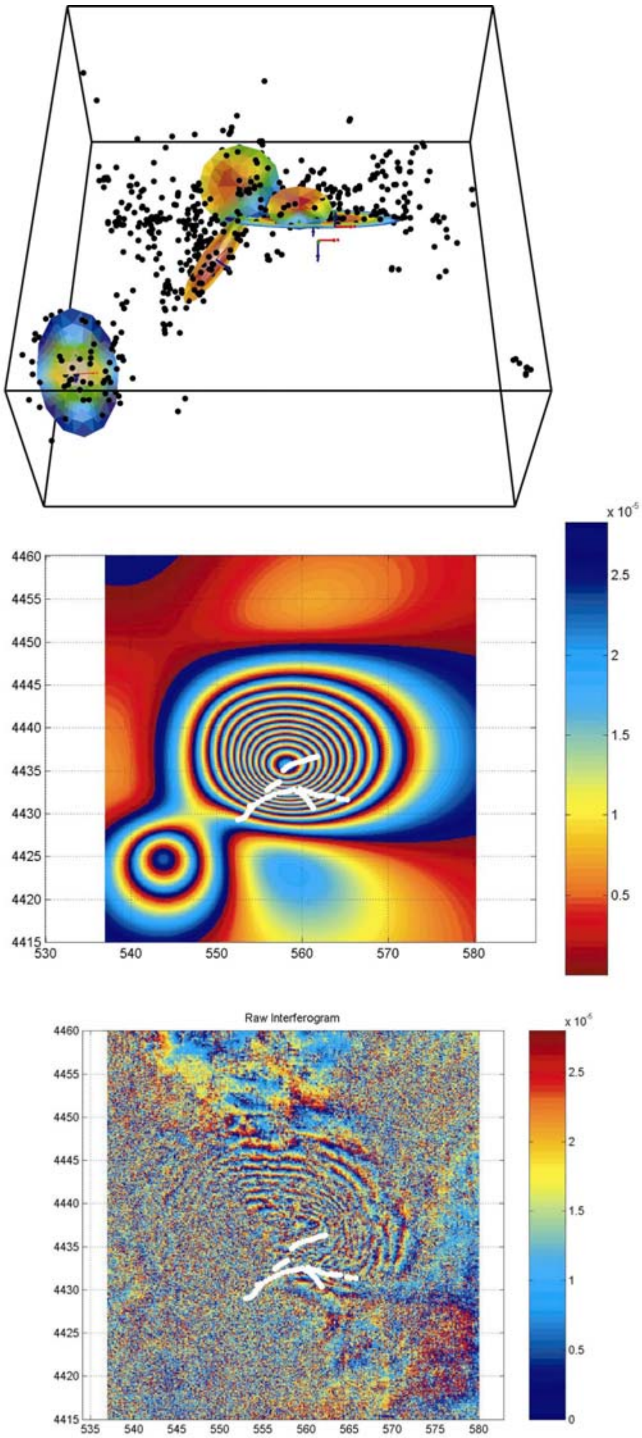

Figure 1. Poly3D Modeling of surface deformation due to the Kozani-Grevena earthquake sequence. **Top:** Poly3D model showing aftershock locations (black dots) and interpreted faults, color coded with relative slip values (red=maximum, blue=minimum). **Middle:** Interferogram calculated from the modeled surface deformation using the fault network shown above. **Bottom:** InSAR imterferogram from Meyer et al. (1996) showing observed deformation due to the Kozani-Grevena earthquake sequence.

In addition to the local network data we have obtained regional seismic network data from the Thessaloniki and National networks that include the foreshocks, the main shock, and large aftershocks from May 13 – September 30, 1995 (>800 events). We are in the process of relocating these data in conjunction with the local network data to obtain a more complete picture of the earthquake sequence. Relocations using the double difference method should be completed by year end 2002.

Poly3DGUI

The power of the C++ language linked with the graphical sophistication of OpenGL and OpenInventor libraries, combined with the emerging of fast PC graphic cards and Gigahertz CPUs, plus the convenience of the laptop computer, demonstrate that it is now both possible and practical to do fast three-dimensional computations and visualizations on a PC running Windows. These activities are no longer restricted to expensive workstations running Unix, and so become accessible to a much larger community of researchers and students. Poly3D Graphical User Interface (Poly3DGUI) uses these technologies to enable real time simulations and visualizations of slip events on many interacting faults with complex 3D geometries. The Windows interface of Poly3DGUI (Fig. 2) has major benefits because it is familiar, easy to learn, efficient to use, and the hardware is inexpensive. The icons, menus, and multiple windows environment are similar to common PC applications.

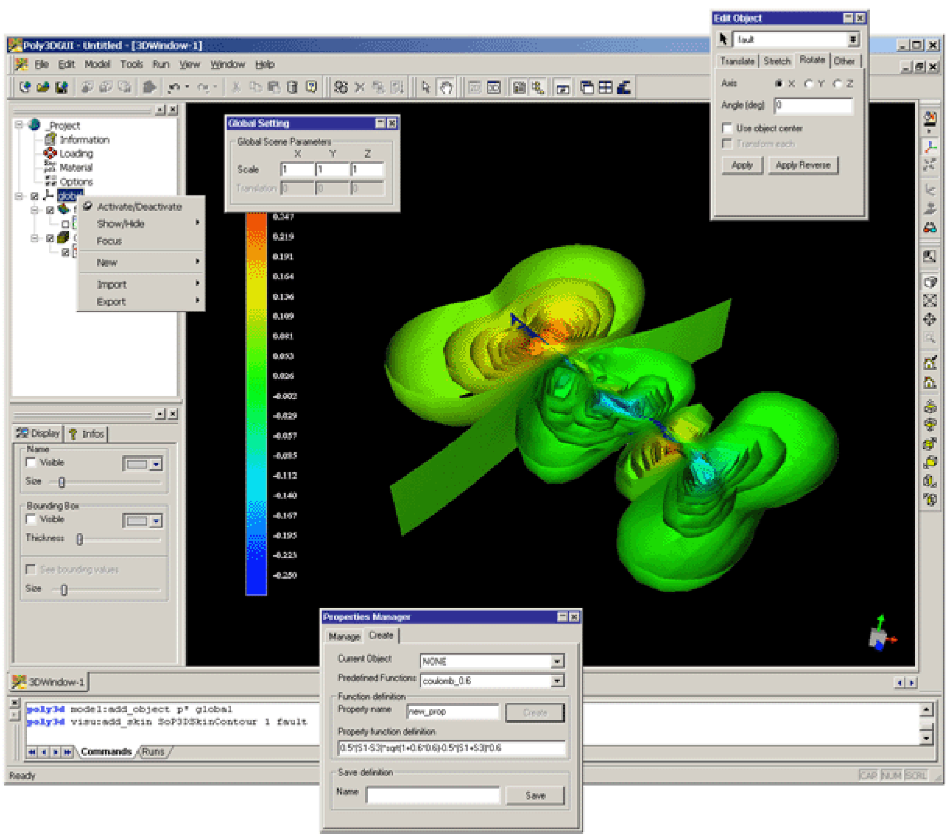

Figure 2: Windows based Graphical User Interface (Poly3DGUI)

The graphical interface was designed with the idea of expandability of functionalities, user customization and wizards, to help the users build a model, apply the boundary conditions, and visualize and analyze the output in three-dimensions in real time at the desktop. Poly3DGUI also permits the construction, editing and visualization of surfaces (using a triangular mesh). It has built-in visualization tools to analyze the output from

Poly3D (the BEM numerical code) such as iso-contours, iso-surfaces and many more, all referred to as "skins" (see Fig. 3).

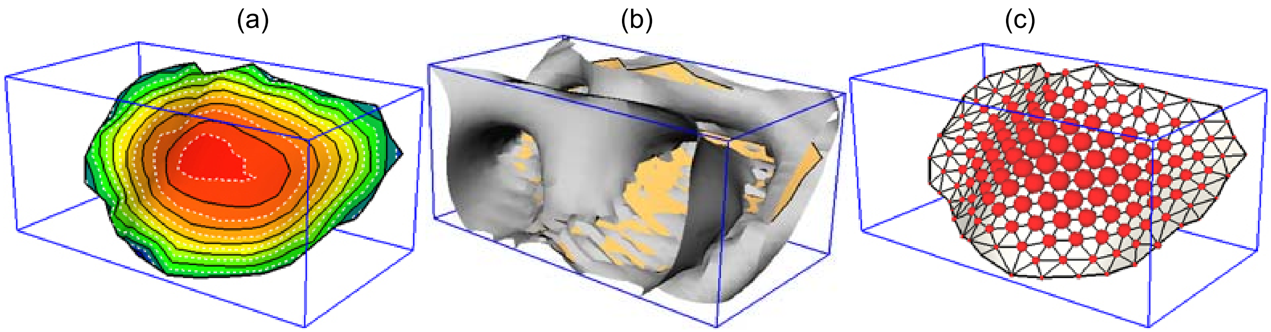

Figure 3: Example of visualization tools (skins). (a) Iso-contours, (b) Iso-surfaces, (c) Point Attribute.

The notion of plug-ins reinforces the robustness of this software by providing specific functionality to users. The fully functional unlimited undo/redo capability helps considerably during a modeling session to eliminate poor choices or mistaken operations from the procedure, and to decrease the time spent in setting up a model. The ability to import standard file formats from other applications, such as seismic interpretation software and fault analyses software, allows these data to be used in Poly3D and manipulated in the user-friendly graphical interface. Planned plug-ins will bring new geometrical algorithms (remeshing, boolean operations, etc.) as well as new "skins" such as Vector-plots, Deformed-surfaces and InSAR representations to the interface.

Poly3Dinv

A new three-dimensional slip inversion algorithm (linear inverse problem), called Poly3Dinv, has been developed. The approach uses the same boundary element method (BEM) as Poly3D that is based on the analytical solution of an angular dislocation in a linear-elastic, homogeneous, isotropic, whole- or half-space. Poly3Dinv employs planar triangular elements of constant displacement to model fault surfaces. Discretization of surfaces into triangular boundary elements allows the construction of complex three-dimensional fault surfaces with irregular tiplines and no overlaps or gaps. Given the geometry of faults as well as observed displacement data (InSAR, GPS), the algorithm inverts for slip distributions on the faults using a Damped Least Squares algorithm for triangulated surfaces. The method and some preliminary results will be presented at American Geophysical Union Meeting, in December 2002. The code is not yet available since it is still in development (prototype).

Non-technical Summary

We are investigating how extension of Earth's crust is accommodated by a system of faults with complex 3D geometries, and how these faults interact in time and space through earthquake events. Relocations of aftershocks from the 1995 Kozani-Grevena earthquake reveals a pattern of faults that apparently trigger one another and act in concert to accommodate regional extension. We model this fault system using the boundary element method (BEM) and the computer code (Poly3D) with a graphical user interface (Poly3DGUI) to provide a user-friendly and versatile numerical modeling tool. This tool is made available to researchers by downloading from our website.

Reports published

[1] FIORE, P, 2002, Structural Relations Between Folds and Thrust Faults: Preliminary Analysis of the Emigrant Gap Anticline, Wyoming. *In D. Pollard & A. Aydin, eds., Proceedings of the Stanford Rock Fracture Project*, v. 13, p. PE.

[2] MAERTEN, F. AND MAERTEN, L., 2002, Poly3DGUI, a new graphical interface for industrial use: architecture and functionality. *In D. Pollard & A. Aydin, eds., Proceedings of the Stanford Rock Fracture Project*, v. 13, p. F1-F4.

[3] MAERTEN, F., MAERTEN, L., RESOR P, 2002, Slip inversion on complex fault surfaces using angular elastic dislocations, *Eos Trans. AGU, 83(47), Fall Meet. Suppl., Abstract G61B-0989*

[4] POLLARD, D., MAERTEN F., MAERTEN L., RESOR P., AND FIORE P., 2002, Forward 3D Modeling of Complex Fault Systems Using an Elastic Boundary Element Method*, GSA Abstracts with Programs Vol. 34, No. 6, Paper No. 112-7.*

[5] RESOR, P, POLLARD, D, 2002, Deformation Associated With A Continental Normal Fault System, Western Grand Canyon, Arizona, *GSA Abstracts with Programs Vol. 34, No. 6, Paper No. 79-4.*

[6] RESOR, P, 2002, The Geometry and Mechanics of a Hanging Wall Anticline, Grand Canyon, AZ. *In D. Pollard & A. Aydin, eds., Proceedings of the Stanford Rock Fracture Project*, v. 13, p. PJ.

Availability of the code

Poly3D and Poly3DGUI for non-commercial users can be downloaded at :
http://pangea.stanford.edu/geomech/Software/Software.htm
(choose “Download” in the left menu).

These programs are provided free of charge to non-commercial users, but Stanford University requires a signed Collaborator License Agreement from each user. This will help us keep track of users, so we can distribute news, bug-fixes, and upgrades.

The non-commercial version of Poly3DGUI works under Windows and was created using Open Inventor, a very powerful object-oriented 3D graphics developer’s toolkit from TGS (www.tgs.com). TGS charges users for single ($150) or multiple runtime licenses. One should contact TGS for ordering runtime licenses. For new users, a 15 days free trial license is automatically attributed.

Poly3D and Poly3DGUI for non-commercial users are node-locked to a particular computer's C drive, so they will execute only on the licensed system using the correct password string. To receive the password information for downloading and installation of Poly3D and Poly3DGUI, please follow these 4 steps:

1. Read and print the Collaborator License Agreement.

2. Provide all the requested information (including the C drive volume serial number of your computer*), and mail or email the signed original to David Pollard (address below).

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3. Upon receipt of the completed and signed Collaborator License Agreement you will be sent an email with the password information necessary to download and install Poly3D** and Poly3DGUI. You will also be sent the license.dat file necessary to operate Poly3D and Poly3DGUI academic on one personal computer.

4. If you are satisfied with Poly3D and Poly3DGUI and want to use these codes beyond the TGS 15 day free trial period, contact TGS (www.tgs.com) for ordering OpenInventor runtime license(s).

(*) To determine the C drive volume serial number of your computer click Start, click Run…, type command, and click OK to open the DOS command window. After the DOS prompt type vol c: and press Enter. Record the Volume Serial Number on the Collaborator License Agreement. Type exit to close the DOS command window.

(**) If you decide to use Poly3D only, you still need to send the completed and signed Collaborator License Agreement. Upon receipt you will be sent an email with the password information necessary to download Poly3D academic.